Rover Autonomy for Long Range Navigation and Science Data Acquisition on Planetary Surfaces

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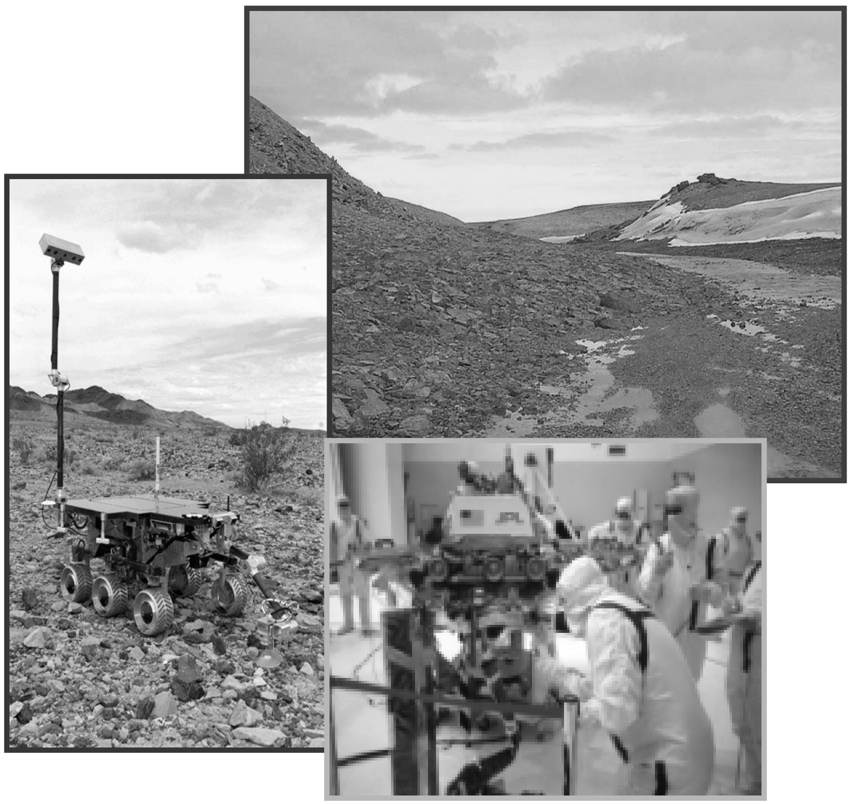


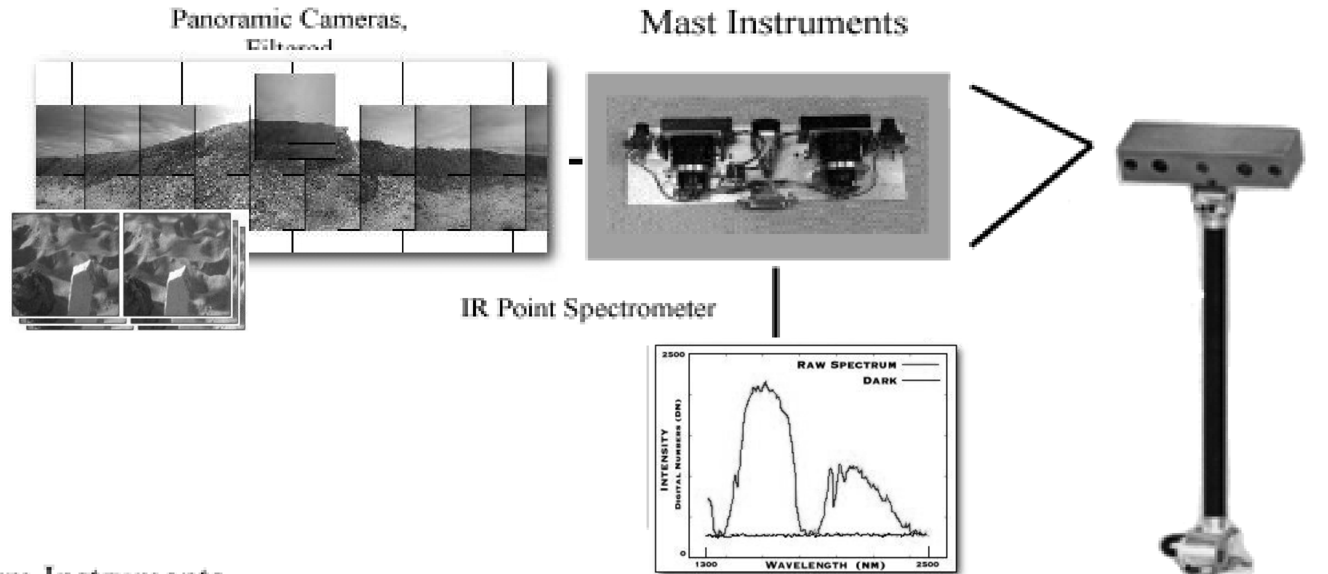
- Reference mission for Mars Smart Lander (MSL) 2009 calls for long, continuous, autonomous traverses on the order of 450 meters.
- Numerous science sites separated by as much as 3 kilometers are planned.
- Mission could last as long as 1000 sols.
- Greater onboard rover autonomy is needed in order to maximize science data return.

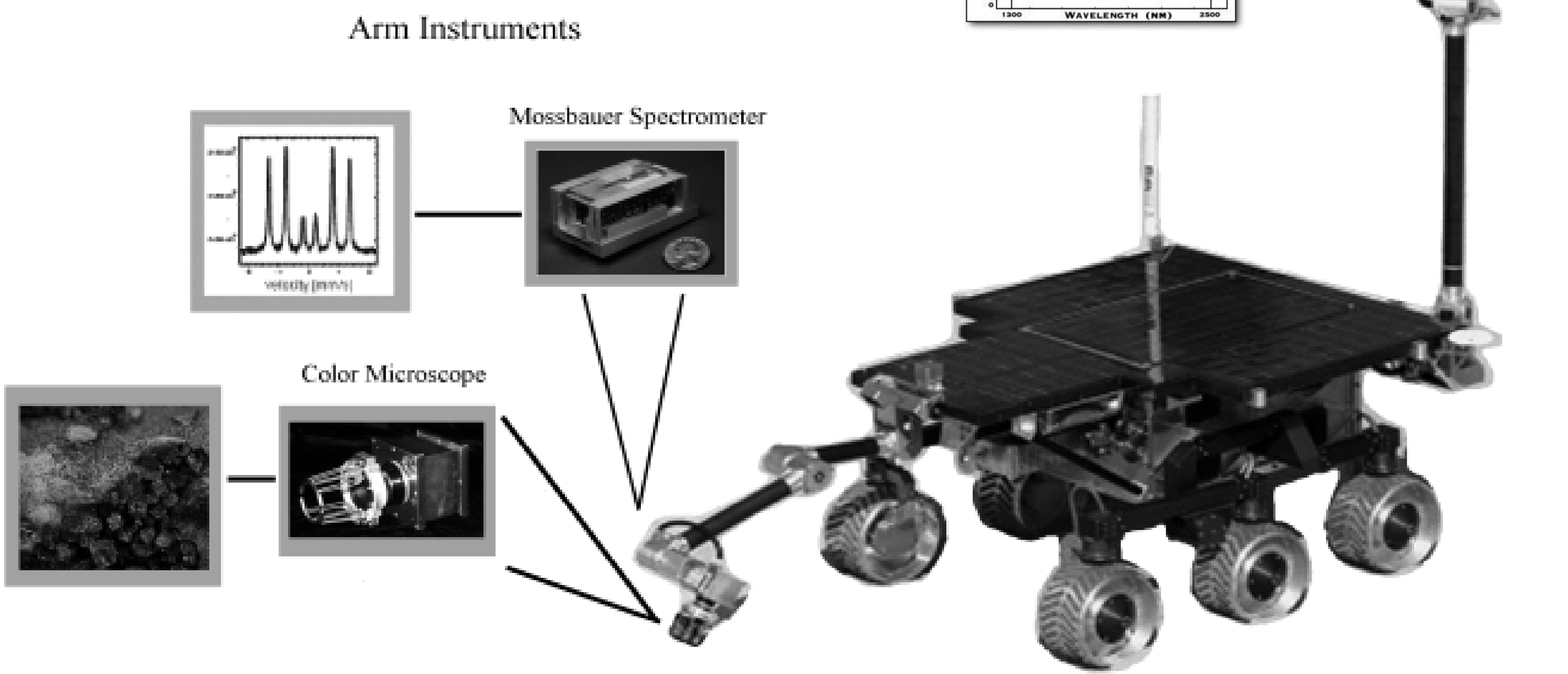
Rover Autonomy

FIDO (Field Integrated Design & Operations) Development Environment

- Multiple JPL technology robots employ this architecture: the MER/Athena-inspired FIDO rover, MER Egress Rover, SRR, Inflatable Rover, Robot Work Crew, LEMUR, ATE, Cliff-bot...
- The FIDO development environment provides reusable software (motion control, stereo processing, guidance, manipulation, user-instrumentation interfaces, etc.)
- Operations of resulting rovers are based in a common mission operations toolset: *WITS* (Web Interface for TeleScience), a distributed and collaborative environment for planning-sequencing and data product downlink, and *Viz* (ARC)
- FIDO field experience to date has shown that these terrestrial system analogs reduce mission risk, providing cost-efficient integrated technology development, testing & evaluation within a flight-relevant environment, with direct flight participation

Miniaturization and Integration of In Situ Instruments on FIDO





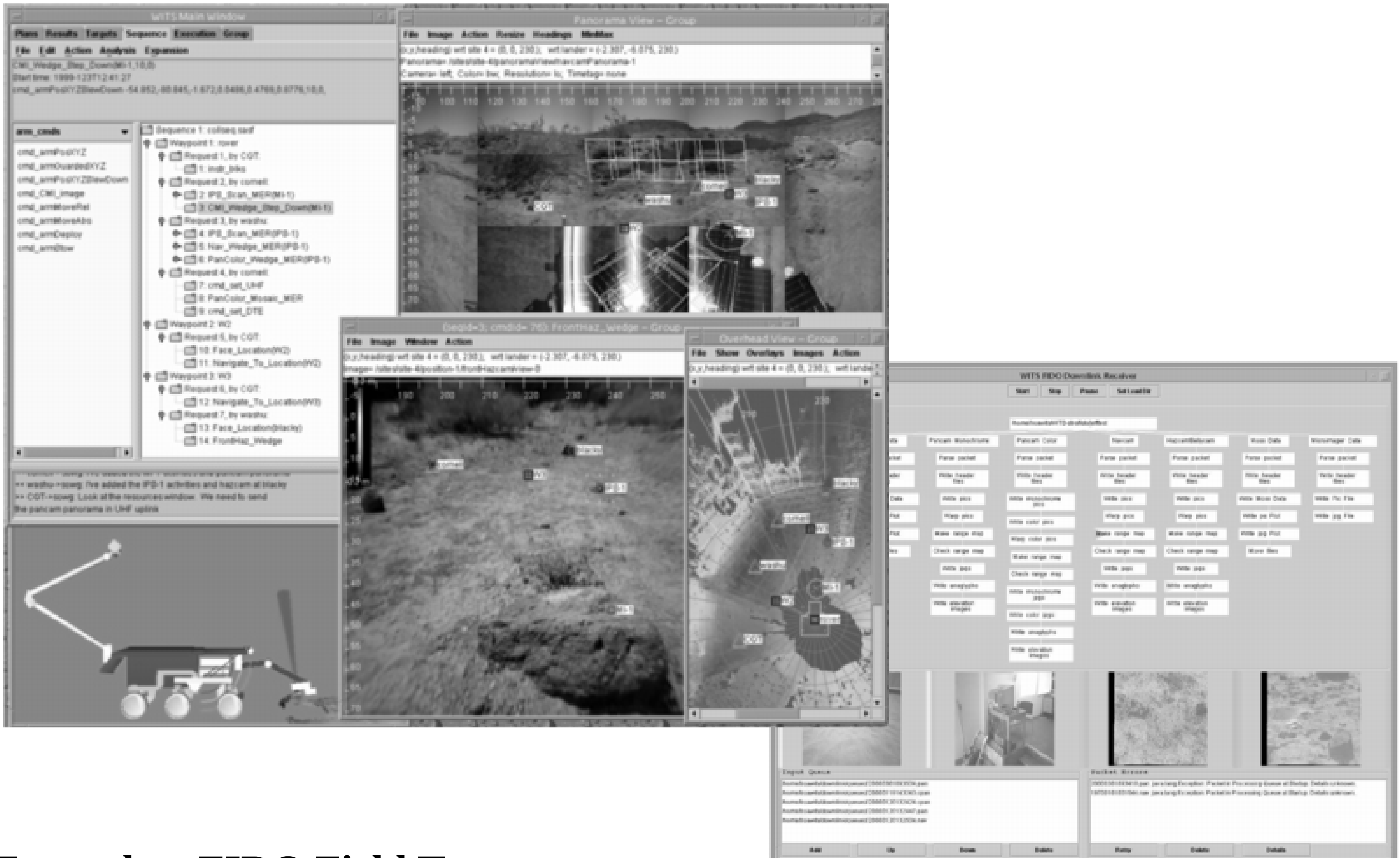
Rover Autonomy

- **Mars Exploration Rover (MER)**
  - mission simulations & science training in realistic terrestrial environments for ops & scenario validation
  - *WITS/*Web Interface for TeleScience selected as the MER science activity planning tool
  - testing interfaces with MIPL for field trial telemetry processing
  - targeted engineering and functional tests (instrument arm, localization repeatability)
  - MarsYard, Arroyo, & field tests in direct support of the MER project
  - FIDO product transfers <u>including personnel</u>

- **Mars Smart Lander (MSL) & Mars Sample Return (MSR)**
  - advancement of “go-to” capability
  - enablement of visual rendezvous/return
  - development of mobile *in situ* sampling
  - technology benchmarking & reporting

Technology & Mission Relevance

Rover Autonomy



Example: FIDO Field Test
Ground Data System (GDS) Interfaces

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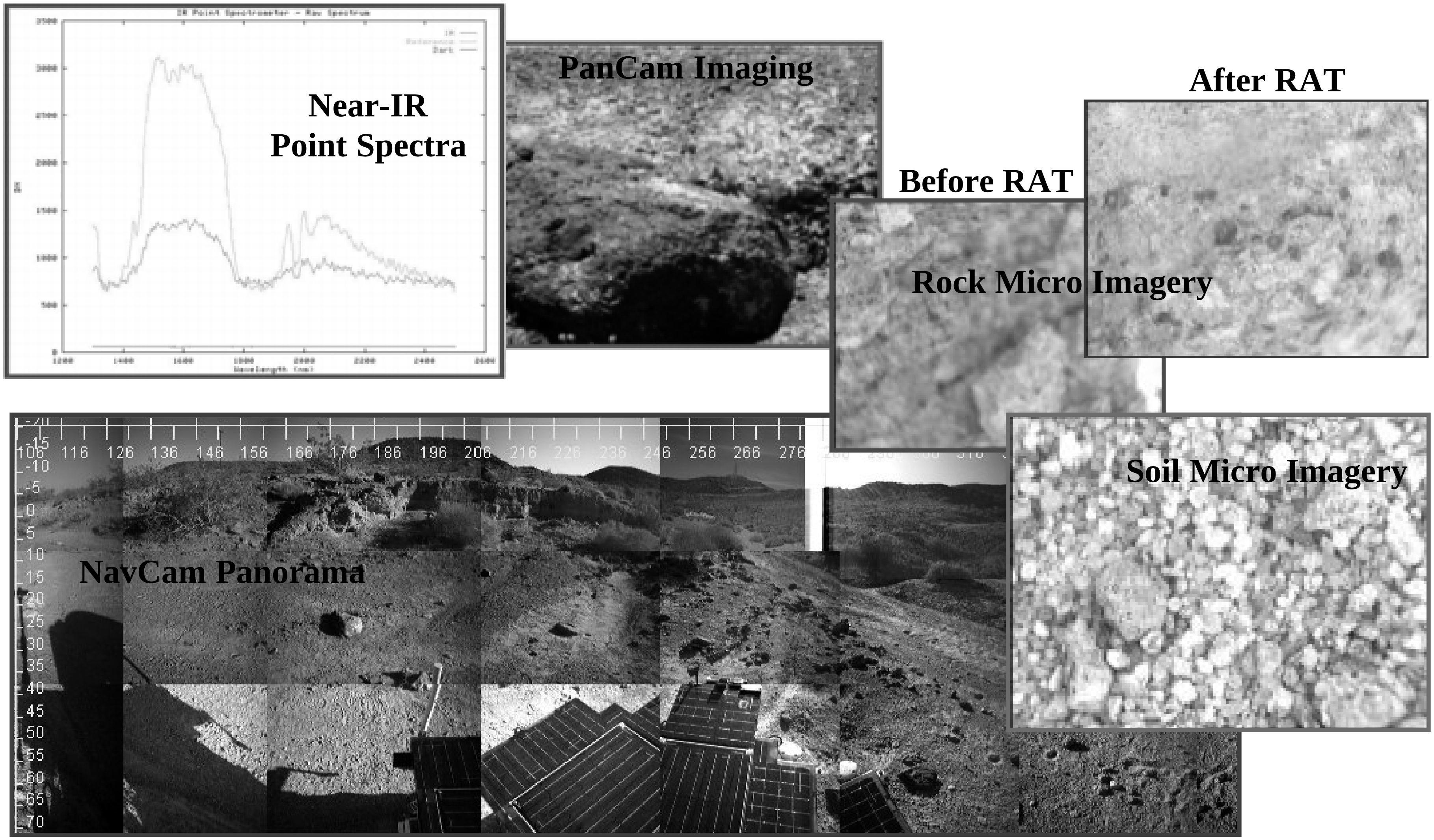

FIDO Field Test Data Products

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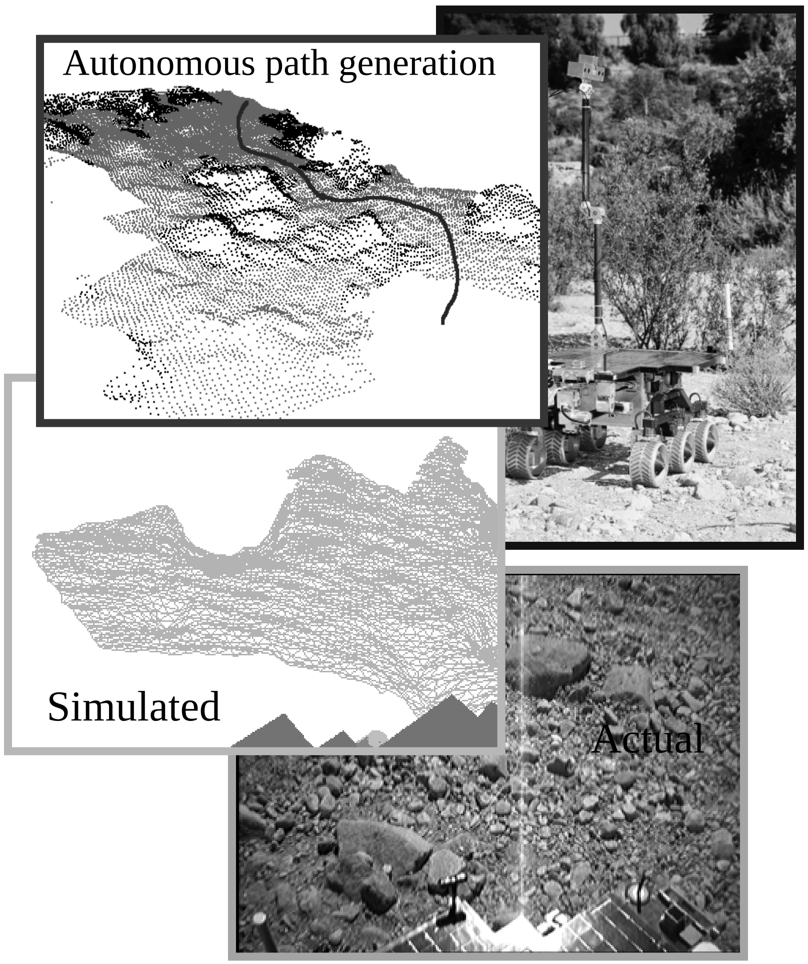
Long Range Navigation

Road Map Navigation (ROAMAN)



• Demonstrated onboard path planning algorithm that autonomously generates a series of waypoints that are passed to the local path planning algorithm (DriveMaps) for obstacle avoidance during long range traverses.

• Both portions of the algorithm use an occupancy grid representation to perform hazard detection and path planning. Map pruning leads to highly efficient path generation.

• Maps that are maintained by the higher and lower level portions of the system are not shared, since there may be substantial localization errors that accumulate during any long traverse.

• Long range path planning is periodically repeated, depending on camera spatial resolution (typically good range data to 12 meters ahead of the rover).

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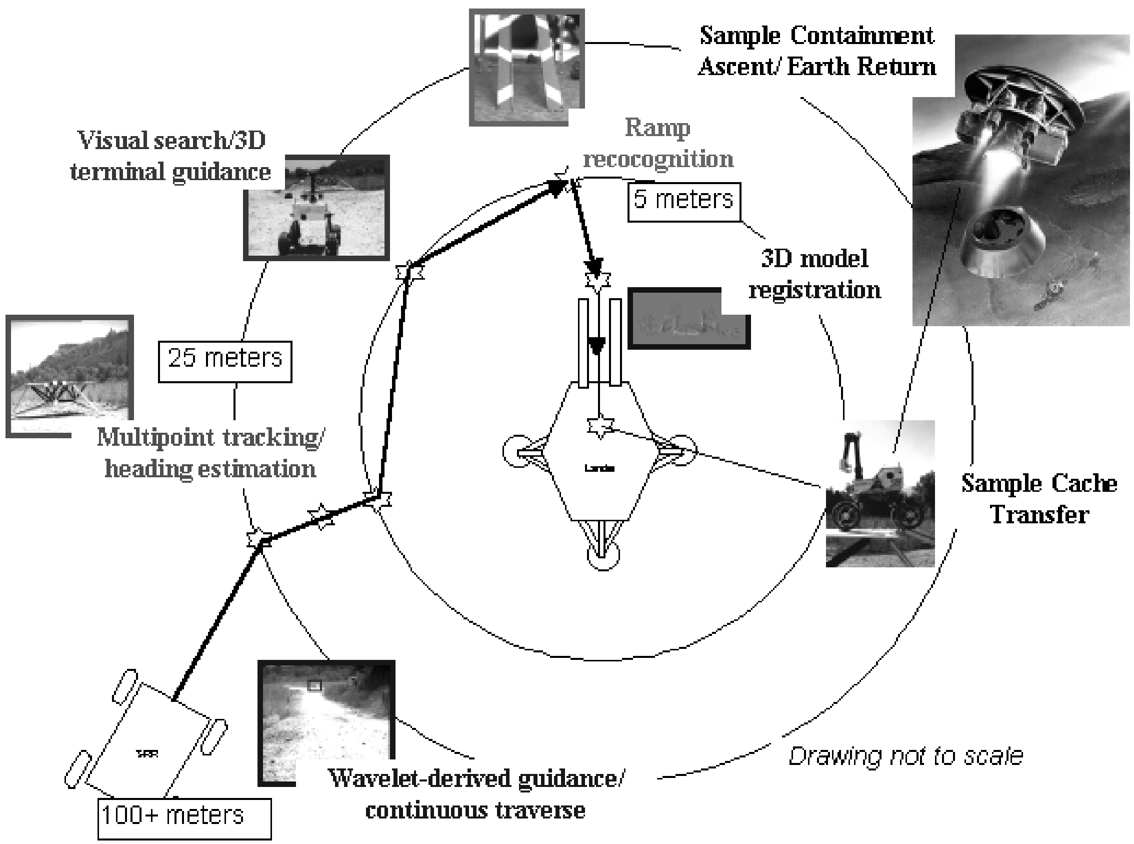
Long Range Rendezvous



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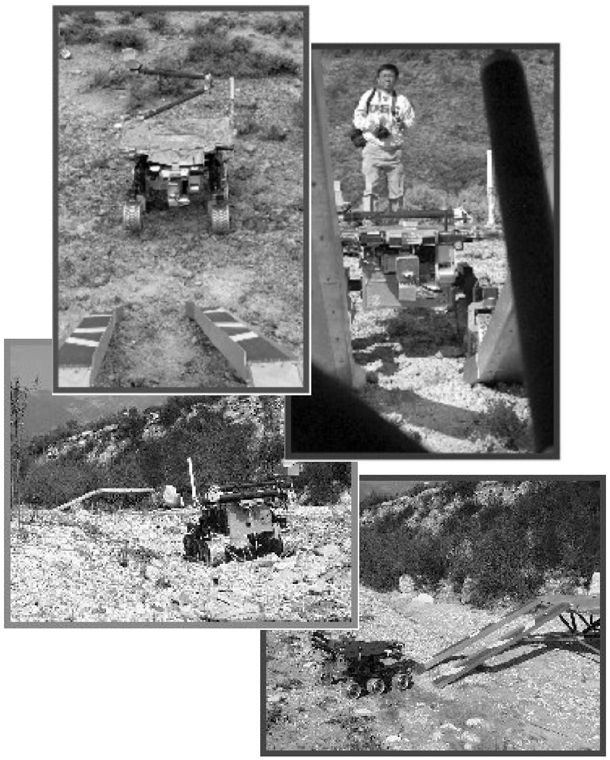
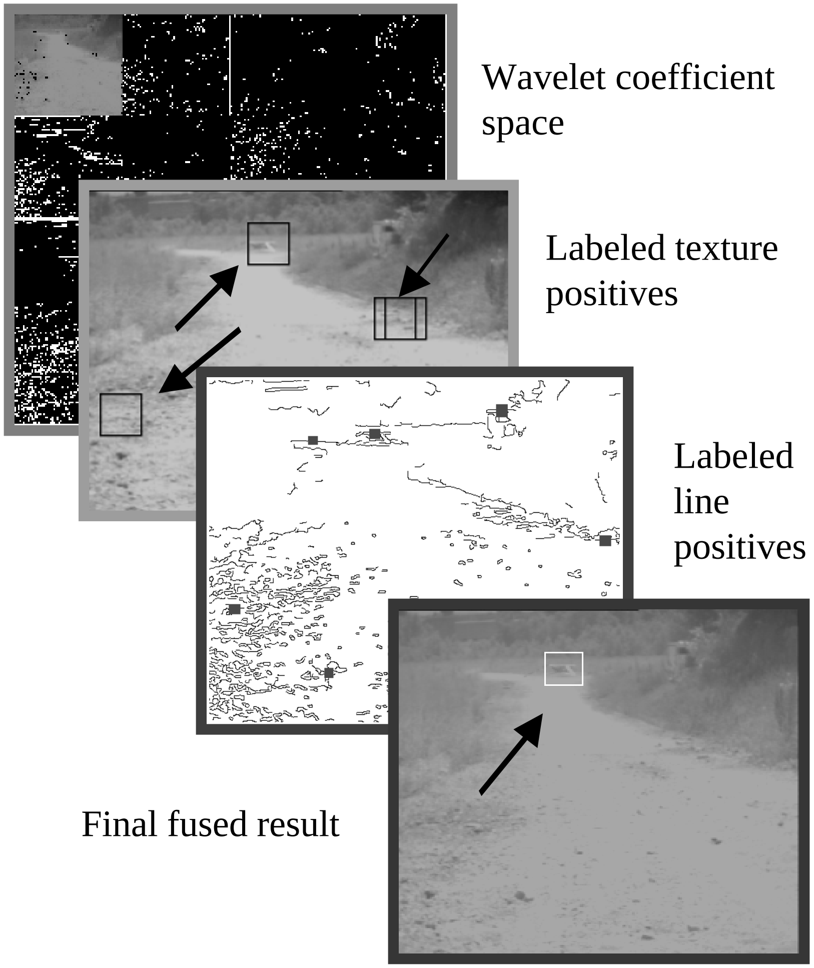
Lander Detection/Rendezvous



- Long range lander tracking/navigation (Fused line and wavelet-derived texture features for target detection, tracking and long-range approach from >100 meters)
- Mid range lander tracking/navigation (Multi-line feature extraction and rover-to-lander pose estimation using known lander geometry for mid-range approach at 5 – 25 meters)
- Lander ramp rendezvous (Pattern extraction, recognition, and precision registered guidance into lander via rover-to-ramp pose estimation on final approach at 0.2 – 5 meters)
- Continuous-motion mobility: high speed hazard detection and avoidance for in-route approaches in non-benign terrain

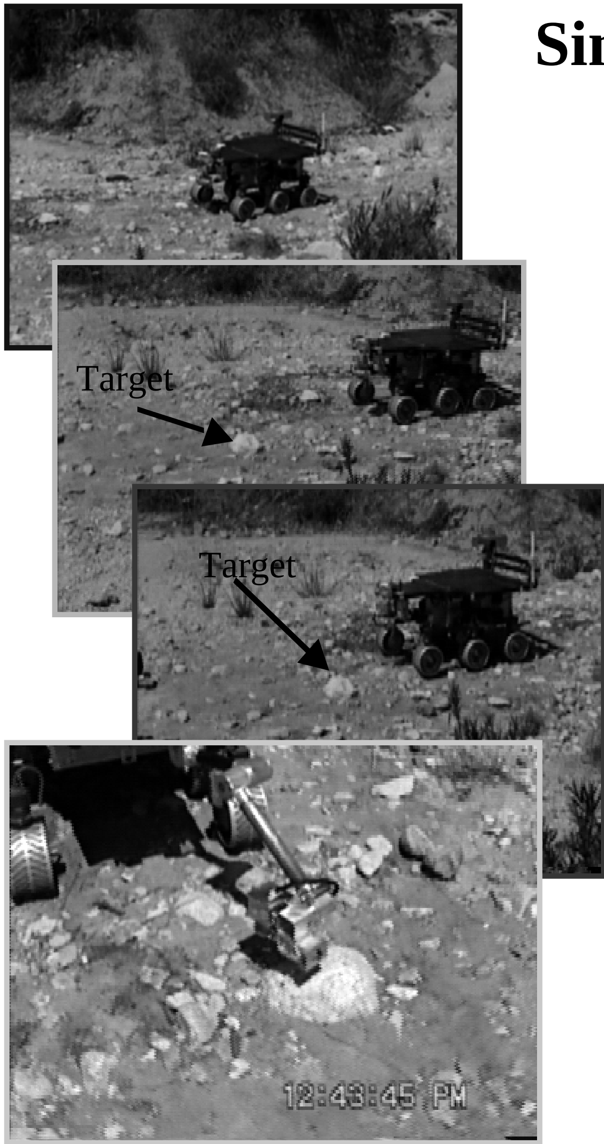
Multifeature Fusion for Long Range Lander Acquisition



Range: 125 Meters

- Lander localization from long distances (125+ meters) using single feature target recognition techniques tends to suffer from false positives due to lack of detail in the lander profile
- *Autonomous multifeature fusion algorithm* uses line features (derived from Canny edge detection) fused with wavelet derived texture signatures to eliminate false positives
- *Angled line detection* gives technique flexibility for other navigation operations in close proximity (detection of lander strut structure)
- *Wavelet derived texture signature* allows fast processing within rover computing constraints
- As illustrated left in a Mars rover to lander approach, this new technique exploits spatial locality of the line and texture features for rapid lander localization in the field of view

Rover Autonomy

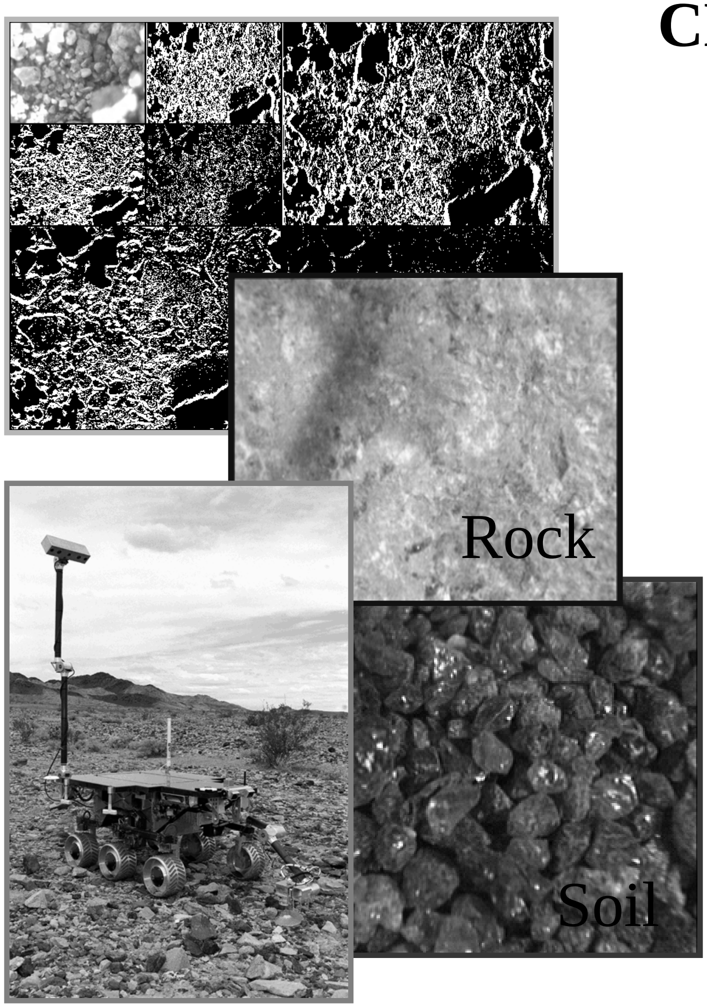


Single Command Science Target Rendezvous

- Demonstrated single command sequence for autonomous approach to specified remote science targets and instrument arm placement on same in Arroyo Seco at JPL.
- Science targets were selected from FIDO navcam panorama using WITS running remotely in Building 82/PRL at JPL.
- 13 step algorithm developed to autonomously track features in vicinity of science targets using combination of cross correlation and homographic transforms.
- Relative position of science target updated during traverse to mitigate errors in localization using wheel odometry.

Rover Autonomy

CMI Auto-Focus



- Demonstrated an autonomous AutoFocus algorithm that determines the optimal in-focus CMI image using a wavelet derived texture index.*
- Instrument arm moved down to target in ten steps of 3 mm each, with focus calculation (~150ms) after each step. Algorithm determines if image is in focus and queues for downlink.
- Extrapolation technique added to algorithm to mitigate errors in range data (typically ~1cm) used for instrument arm placement [leads to out-of-focus images taken too high above target].
- Slope of index within final 1cm of travel is used to extrapolate to correct in-focus point before image acquired.

***** F. Espinal, T.L. Huntsberger, B. Jawerth, and T. Kubota, "Wavelet-based fractal signature analysis for automatic target recognition," *Optical Engineering, Special Section on Advances in Pattern Recognition*, 37(1), 1998.

Experimental Studies

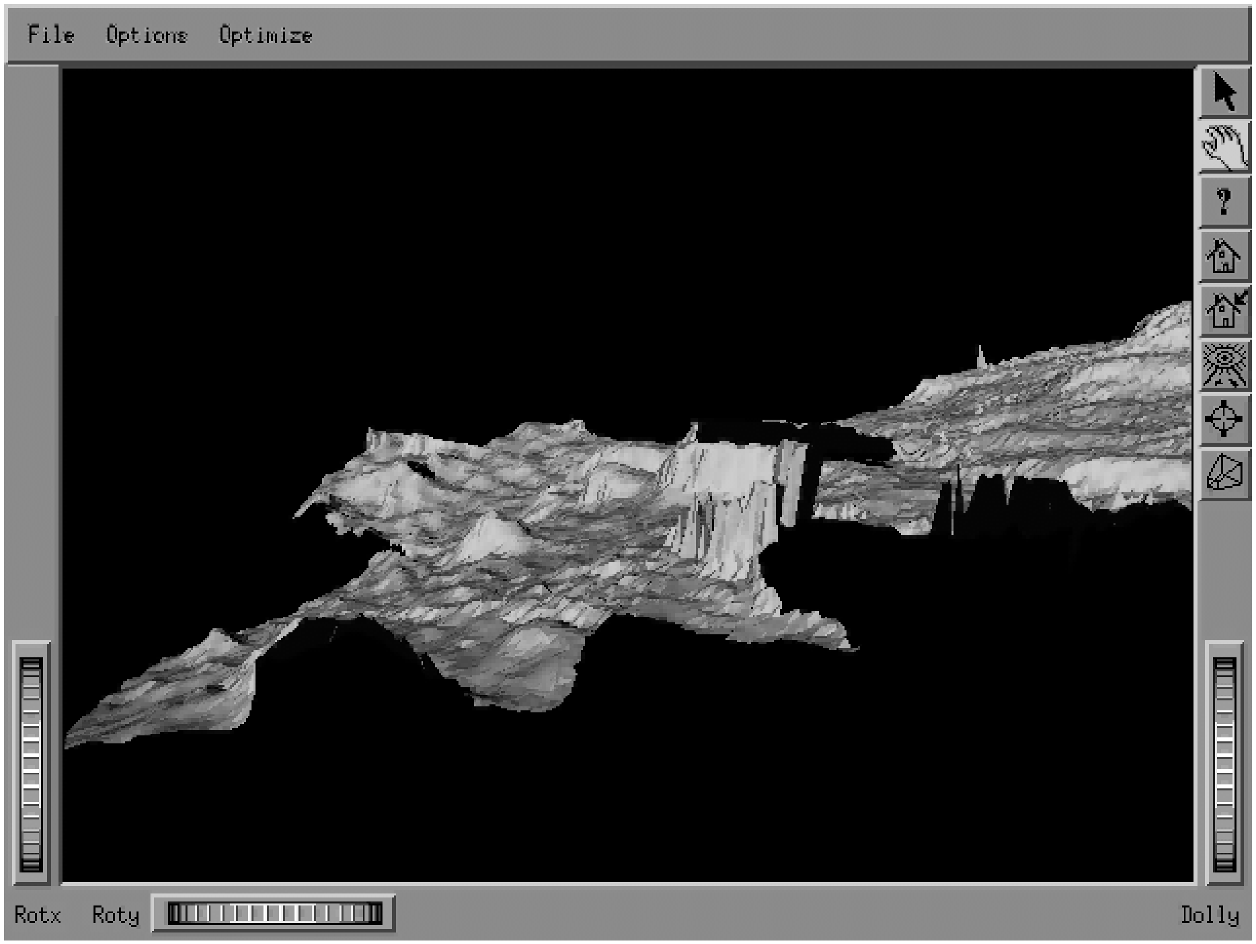
Long Range Navigation

Summary

- **FY99**: SilverLake, CA field trial - 97 meter continuous traverse under autonomous navigation and hazard detection/avoidance control with localization error of 2.5 meters.
- **FY00**: Black Rock Summit, NV field trial - full integration of sun sensor into extended Kalman filter framework with localization errors of 1-2% for traverses.
- **FY01**: Soda Mts, CA field trial - total traverse of 135 meters under autonomous navigation and hazard detection/avoidance control with longest continuous autonomous traverse achieved of 40 meters and an average traverse speed was 60 meters/hour
- **Sept'01**: JPL Arroyo Seco Technology Demo - total traverse of 60 meters in 5 separate runs with autonomous way point generation under autonomous navigation and hazard detection/avoidance control

Rover Autonomy

Long range terrain map -- Arroyo Seco near JPL



Long Range Rendezvous

Summary

- **May’00**: Successfully integrated and demonstrated during the FIDO May ‘00 field trial at Black Rock Summit, NV, a rover terminal precision rendezvous capability - the autonomous visual detection of and guidance to lander ramps from 5m.
- **Sept’00:** Successfully integrated and demonstrated during the FIDO Sept’00 test in the Arroyo Seco at JPL, the mid-range (5–65m) and long-range (65-100m) lander guidance algorithms – the autonomous visual detection of the lander, and traverse over uneven terrain to the terminal guidance standoff point.
- Average long range heading error was <0.5°, average mid-range distance error was <6.5%, and average close range ramp alignment error was < 2cm.

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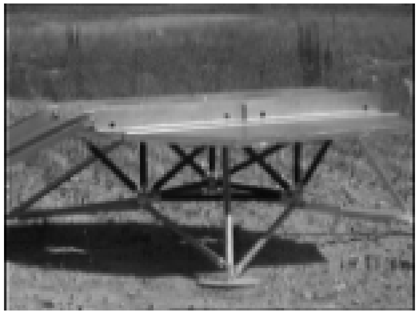
Mid-range Lander Acquisition and Distance Estimates



15 m vs. 14.87 m

25 m vs. 24.50 m

35 m vs. 38.36 m

45 m vs. 42.17 m

* Notes: the left numbers are the true distances and the right numbers are the estimated distances

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Long Range and Middle Range Test

T. Huntsberger et al., 05/02

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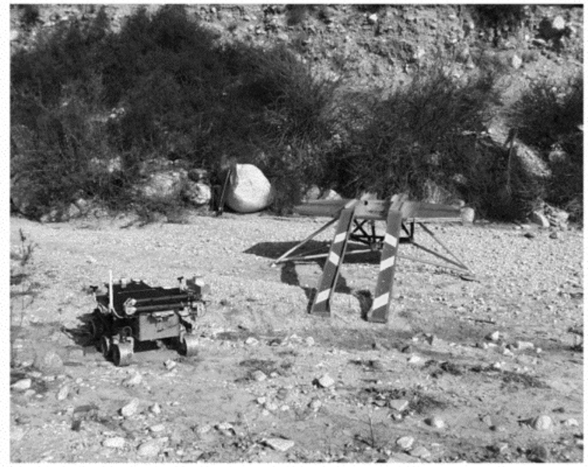

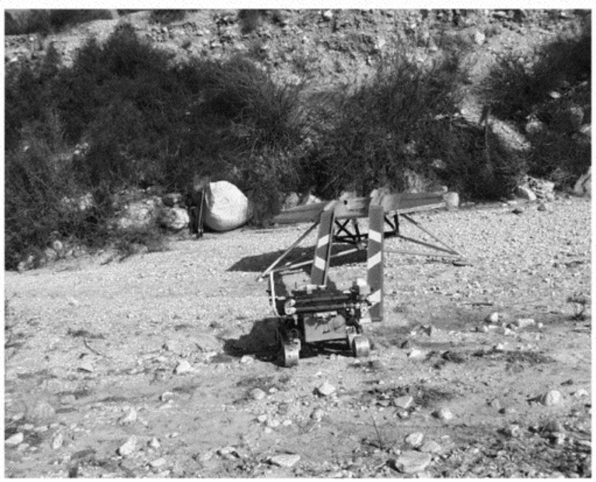

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Ramp Alignment Test

Black Rock Summit, Nevada, May 18, 2000

Rover Autonomy

Black Rock Summit, Nevada, May 18, 2000

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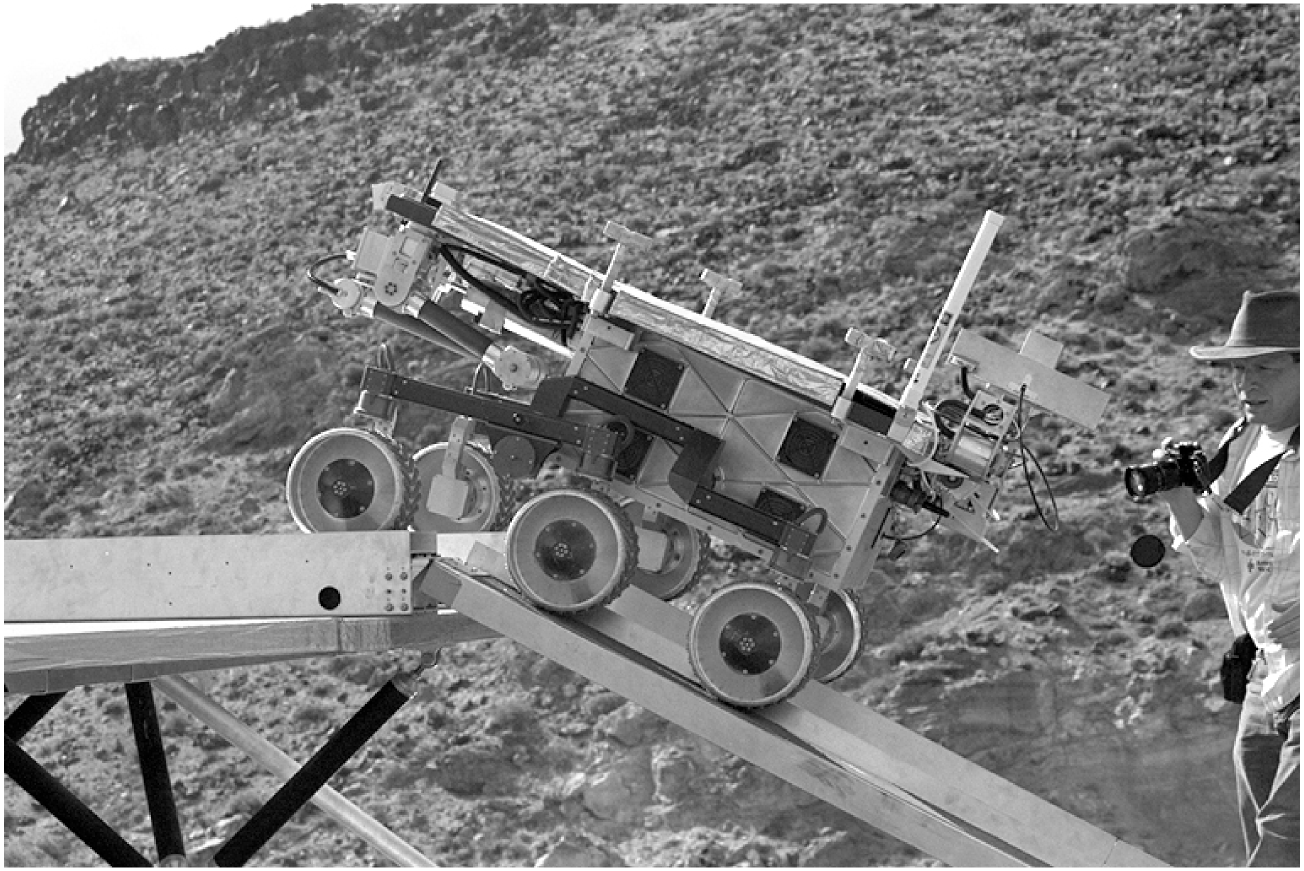

Single Command Science Target Rendezvous

Summary

- 11 runs with an average autonomous approach of 5.9 meters and average instrument arm placement error of 7.5cm (1.3%).
- Error in wheel odometry for rover traverse over same terrain was 92.63cm (15.7%).
- CMI (color micro-imager) Auto-Focus and extrapolation capabilities are completely integrated into Auto-Approach sequence.
- Independent Auto-Focus Tests: 100%/82% success for 50/10 tests on soil/rock samples.

Initial Panoramic Wedges

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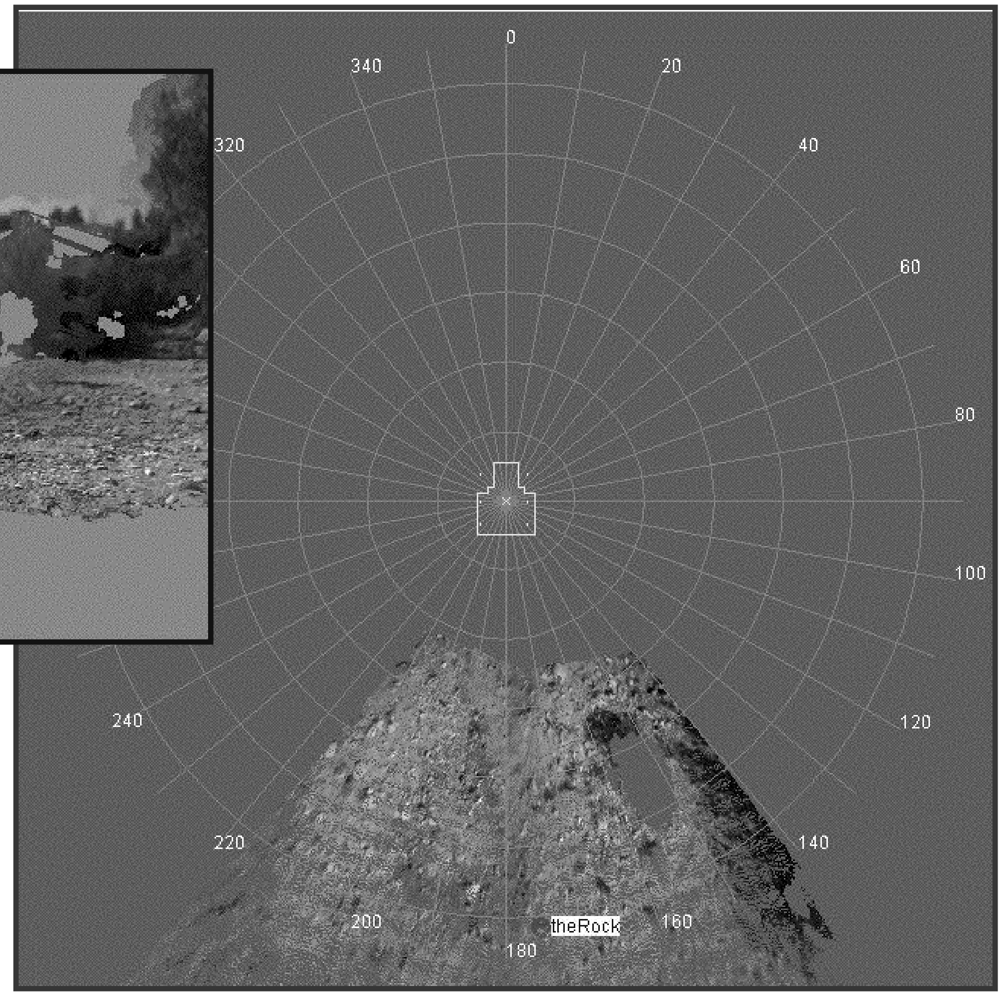
Science Target Selection



3D (above) and overhead (right) WITS views of target selection

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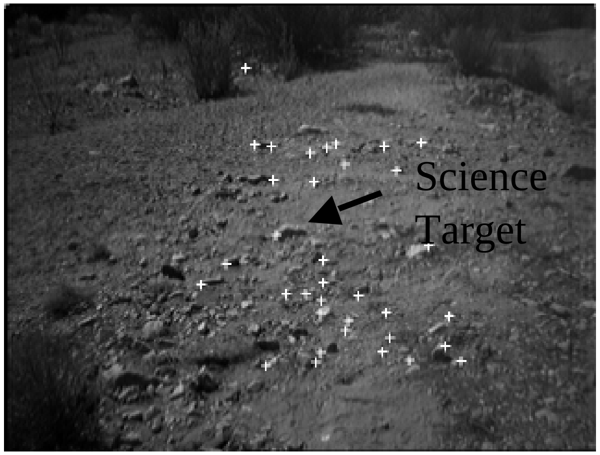
Auto-Approach Feature Tracking



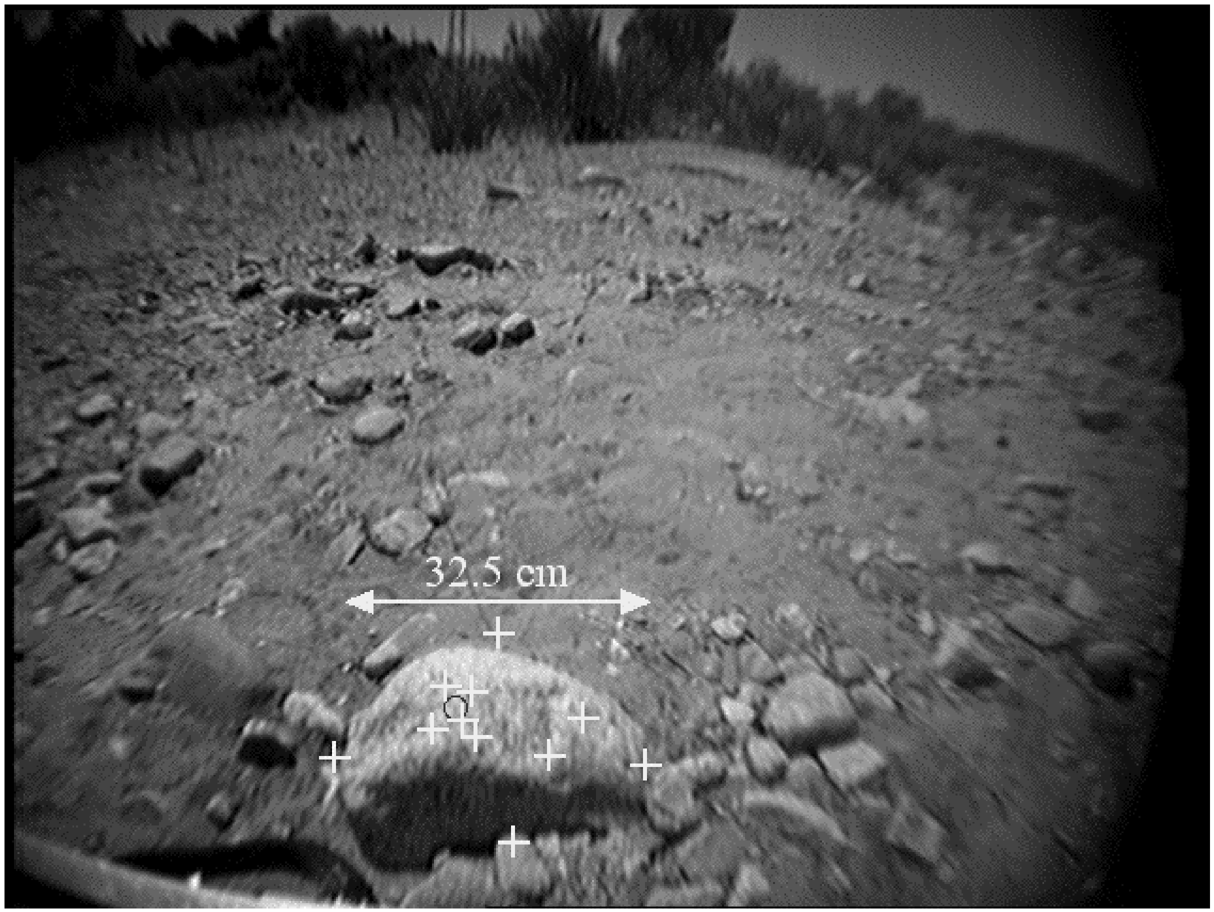
6.17 meters

5.00 meters

3.83 meters

2.66 meters

Placement Results (11 Trials)

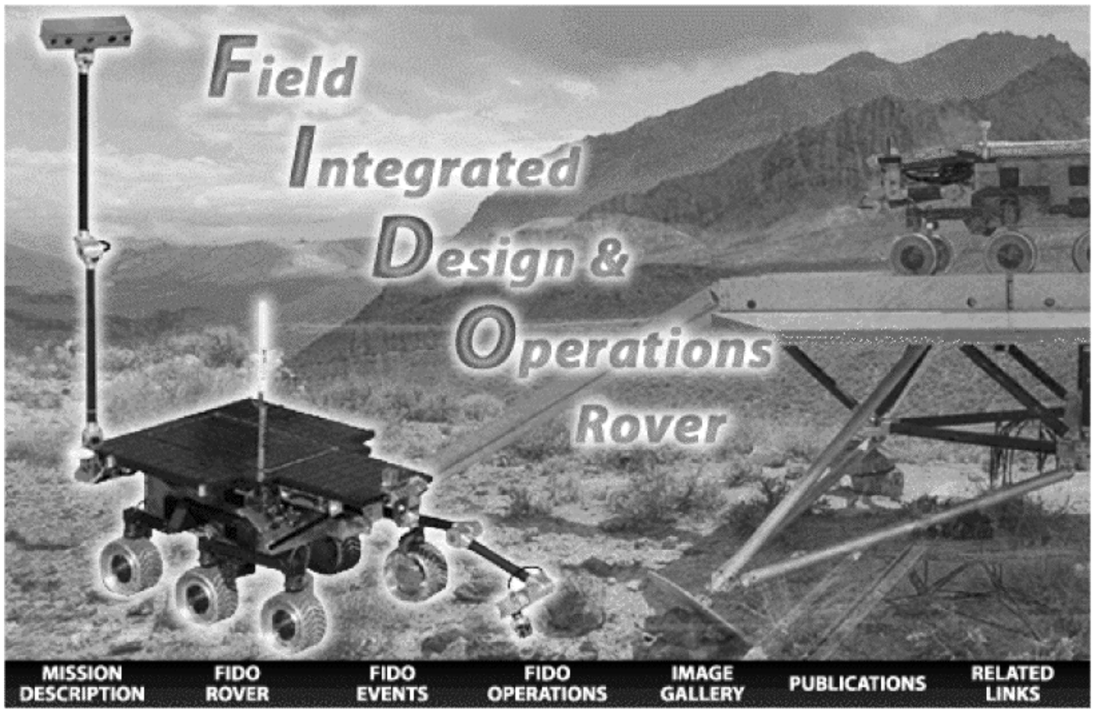


Red circle is nominal target

Rover Autonomy

FIDO Web Site: http://fido.jpl.nasa.gov

- Provides a comprehensive collection of high-level documentation about the FIDO Testing task, the FIDO rover and the FIDO infrastructure



- Web site access is on a steady increase; over 1,500,000 hits registered since the spring FY2001 MER/FIDO field trial...